FBG Dispersion Compensation in a 43 Gbit/s WDM System: Comparing Different FBG Types and Modulation Formats

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ABSTRACT

Within this contribution the impact of phase ripples and amplitude filtering induced by fiber Bragg gratings (FBGs) for in-line dispersion compensation in optical long-haul wavelength division multiplex (WDM) transmission systems is investigated. The goal is to evaluate the possibilities and limitations of employing FBGs instead of dispersion compensating fiber (DCF) in modern communication systems with certain upgrade issues. The considered upgrade scenarios contain the increase of the data rate from 10.7 Gbit/s to 43 Gbit/s and employment of other modulation formats than conventional NRZ-ASK (non-return-to-zero amplitude shift keying), such as optical duobinary (ODB) and differential phase shift keying (DPSK). Moreover, the performance of channelized FBGs and broadband FBGs is compared for these scenarios.

Since the FBGs' frequency and phase responses include stochastical components the investigations are performed by extensive statistical simulations. These simulations are based on measured group delay and insertion loss characteristics of numerous FBG samples. The results show performance limitations for channelized FBGs due to amplitude filtering and strong phase ripples at pass band edges, especially if ASK or DPSK modulation is applied. The broadband FBG offers significantly better transmission characteristics.

Keywords: dispersion compensation, fiber Bragg gratings (FBG), phase ripples, modulation formats, WDM

1. INTRODUCTION

Dispersion compensating FBGs have a good prospect to replace the commonly used DCF in optical long-haul transmission systems. Offering low insertion loss together with negligible nonlinearities, FBGs are an interesting alternative for system design [1]. Moreover, they are smaller in size and more cost effective in production. The main drawback of FBGs is that the transmitted signal suffers from imperfections in their group delay characteristics, known as group delay ripples (GDRs). GDRs result in a distortion of the FBG's phase response ("phase ripple") [2]. The influence of the phase ripple depends on the modulation format, the data rate, as well as the shape of the ripple and the FBG type [3-4]. The feasibility of replacing DCF in a 10.7 Gbit/s system by FBGs has been shown in [5]. In this paper a general approach is used to find out, if an upgrade from 10.7 Gbit/s to 43 Gbit/s in a system with dispersion compensating FBGs is possible and for which kind of FBGs. Moreover, it is investigated, whether channelized or broadband FBGs should be used to replace DCF in an existing 43 Gbit/s WDM system. Since the upgrade might not be possible for the conventional On-Off-Keying format (NRZ-ASK) other formats are investigated as well. The choice of modulation formats is guided by the aim of keeping the upgrade effort small.

2. SIMULATION SETUP

The simulation setup is shown in Fig. 1. WDM transmission with 100 GHz channel spacing at 43 Gbit/s over up to 20 spans of 80 km standard single mode fiber (SSMF) is performed. To account for inter channel impairments in multichannel WDM systems it is sufficient to consider two neighboring channels at each side of the investigated channel, hence only five channels are simulated. Each channel carries a pseudo random binary sequence (PRBS) with the length 1024 bits. In order to provide uncorrelated data, the sequences within the outer channels are shifted cyclically by a random number of bits with respect to the sequence of the inner one. Employed modulation formats are NRZ-ASK, DPSK with NRZ and return-to-zero (RZ) pulse shape (NRZ-DPSK, RZ-DPSK) and ODB. The RZ pulses exhibit a duty cycle of 50%. The three-level duobinary signal is generated by low pass filtering of the differential pre-coded binary signal in the electrical domain (Bessel filter, 5. order, 3-dB-bandwidth: 0.25·data rate). NRZ-ASK serves as a reference, while the other formats are taken into account as possible upgrade options. The input power per span and per channel is varied from -3 to 3 dBm. Dispersion compensation with slope-matched FBGs is applied after each span, with a slight under-compensation for each span. Pre-compensation is not deployed. Since only the influence of phase ripples and not the influence of insufficient dispersion matching shall be considered, the dispersion characteristics of each measurement sample is adjusted to the target values. Two FBG types are applied, namely a channelized FBG with a free spectral range of 100 GHz and a broadband FBG that offers linear group delay over the whole C-band. The channelized FBG offers individual pass bands with piecewise linear group delay for each WDM channel. It is known to work well at 10.7 Gbit/s transmission [5]. Here, the applicability for 43 Gbit/s systems is investigated. Both FBGs are designed for approximately 50 WDM channels.

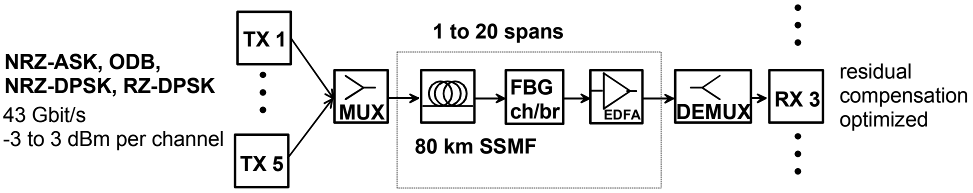

Figure 1: Simulation Setup, WDM transmission for different modulation formats and FBG types (ch: channelized, br: broadband).

The FBGs' phase and frequency responses are extracted from group delay and insertion loss measurements of approximately 100 individual samples of FBGs per type. Fig. 2 a) exemplarily shows the magnitude of the frequency response and the group delay characteristics of a channelized FBG for one WDM channel. The 3-dB-bandwidth of different FBGs and channels is spread between 55 GHz and 77 GHz. The mean bandwidth of all channels and all FBGs is 65 GHz. For smaller bandwidths the amplitude filtering is the most important impact, for broader bandwidths, the huge phase ripples at the edges have a severe influence on the signal. Fig. 2 b) shows the frequency response and the group delay characteristics for the broadband FBG with respect to the same frequency range. It can be seen that the channelized FBG shows stronger phase ripples at the pass band edges, while the broadband FBG's ripples are nearly equally distributed over the whole bandwidth of the FBG. Moreover, they are smaller in amplitude. However, the channelized FBG shows a lower insertion loss of about 1.5 dB (mean center insertion loss of all pass bands of all FBGs) in comparison to the broadband FBG with 3.1dB (mean insertion loss of all FBGs). For comparison Fig. 2 c) and d) show the signal spectra of all considered modulation formats. It can be presumed that especially RZ-DPSK will suffer from the FBG filtering. Since the exact transmission characteristics vary from FBG to FBG and from channel to channel, 20 different combinations of 20 FBGs of each type are chosen randomly from the measurement values for the 20 spans. For each combination three different wavelengths are chosen for the center channel of the five WDM channels, one at each side of the total transmission band of the FBG and one in the middle. This results in 60 different FGB transmission setups per FBG type (20 combinations x 3 WDM channels). At the receiver side the five WDM channels are demultiplexed and the residual dispersion is optimized by evaluation of the eye opening for the center channel. At the optimum residual dispersion, the required optical signal-to noise-ratio (OSNR) at a bit error rate (BER) of $5 \cdot 10^{-4}$ is calculated by an estimation method based on a $\chi 2$-distribution [6]. For comparison of the modulation formats the OSNR penalty relatively to the required back-to-back OSNR is determined.

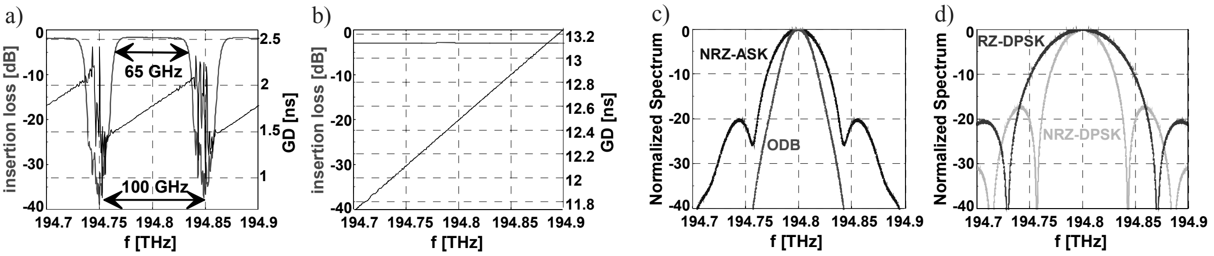

Figure 2: Typical measured insertion loss (left ordinate) and group delay (GD, right ordinate) for channelized FBG (a) and broadband FBG (b). Within simulations ~100 different samples with similar characteristics are applied. Spectra of investigated modulation formats: c) NRZ-ASK and ODB, d) NRZ-DPSK and RZ-DPSK.

3. RESULTS AND DISCUSSION

3.1 Channelized FBG

Figure 3 shows the mean penalty over all 60 setups for all investigated modulation formats and the channelized FBGs. With a fiber input power of -3 dBm for NRZ-ASK after 10 spans the BER of $5 \cdot 10^{-4}$ cannot be achieved for some FBG anymore. Therefore the curve is only plotted up to this value. For other formats this case is reached after some more spans. However, it can be seen that NRZ-ASK, NRZ-DPSK and RZ-DPSK behave very similar – the penalty increases intensely with the number of transmission spans. ODB shows much slower penalty rise and a longer feasible transmission distance. If the input power to the fiber is increased to 0 and 3 dBm per channel (Fig. 3 b) and 3c)) the transmission reach of NRZ-ASK, NRZ-DPSK and RZ-DPSK does not change. This shows that the transmission is limited by phase ripples and filtering, but not by fiber nonlinearity.

To illustrate the spread of the OSNR penalty, Fig. 4 shows the probability density function (PDF) of the penalty after six transmission spans.

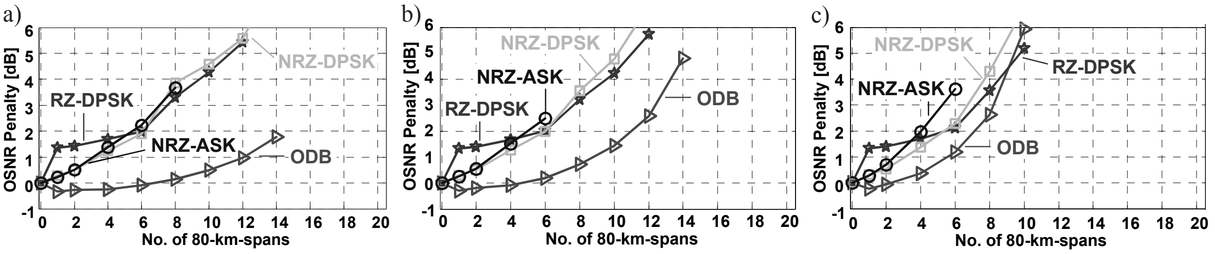

Figure 3: Penalty vs. spans for channelized FBG: a) -3 dBm/span b) 0 dBm/span c) 3 dBm/span.

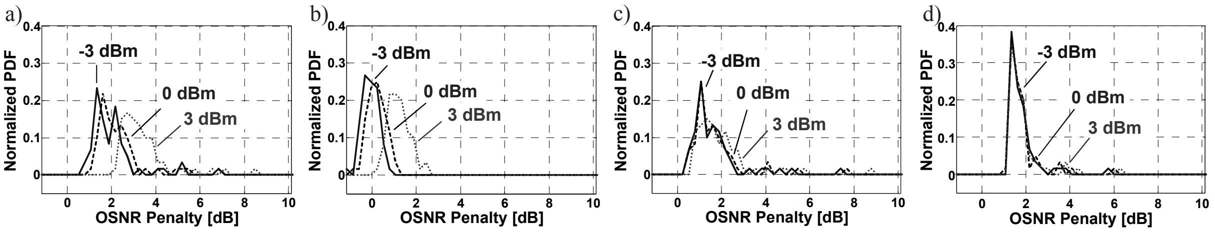

Figure 4: Probability density function of the OSNR penalty after six spans with channelized FBG dispersion compensation for different fiber input powers: a) NRZ-ASK b) ODB c) NRZ-DPSK d) RZ-DPSK.

Since the phase ripples at the pass band edges are increasing, modulation formats with a broader spectrum are more affected. Moreover, the pass bands are not ideally centered round the channel center frequencies. Thus, the concatenation of FBGs leads to a smaller residual bandwidth than 65 GHz. The best cases still offer a bandwidth of 60 GHz after 20 spans. In the worst cases the bandwidth is reduced to 40 GHz after 20 spans. To clarify whether degradation for NRZ-ASK, NRZ-DPSK and RZ-DPSK results from ripples or amplitude filtering, ripple influence and amplitude filtering are simulated separately. The FBG choice is exactly the same as for upper simulations. All fibers are considered as linear. Therefore the input power per span and per channel has no influence. Figure 5 shows the results for both cases. For NRZ-ASK filtering and phase ripples lead to nearly the same amount of penalty. NRZ-DPSK with a similar spectral width (see Fig. 2) shows more tolerance to phase ripples, but more sensitivity to filtering. The step of the RZ-DPSK curve after one span in Fig. 3 results only from filtering not from ripple distortions. However, RZ-DPSK seems a bit more sensitive to phase ripples than to filtering. For ODB the amplitude filtering gives a small improvement, which is a well known property of this modulation format [7]. It is also sensitive to phase ripples, but because of the narrow spectrum it does not experience distortion due to the strong phase ripples at the pass band edges.

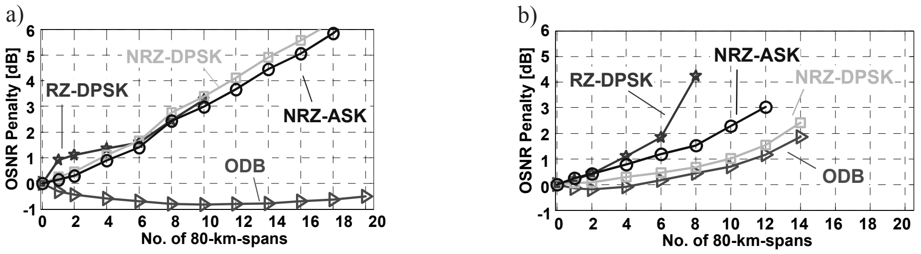

Figure 5: Channelized FBG: Only FBG filter shape without ripples, OSNR penalty vs. spans.

3.2 Broadband FBG

Figure 6 shows the OSNR penalty for the broadband FBG. For low input power a penalty of 1.7 dB is observed for ODB and NRZ-ASK after 20 spans, whereas the results for DPSK yield an even better performance. The main reason why the penalty induced by the broadband FBG is significantly lower than that of the channelized is that no amplitude filtering is applied by the broadband FBG and the phase ripples are nearly equally distributed over the whole transmission band. This makes the broadband FBG very suitable for broader signal spectra. For higher input powers a distinct power dependency of the OSNR penalty can be observed. However, the similar behaviors of NRZ-ASK and ODB and NRZ and RZ-DPSK, respectively, are maintained. Figure 7 shows the PDFs of the OSNR penalty after ten spans. A strong penalty variation can be observed for ODB and NRZ-ASK which might results from penalty due to interaction of phase ripples and fiber nonlinearities. In contrast, DPSK provides a higher tolerance towards fiber nonlinearity.

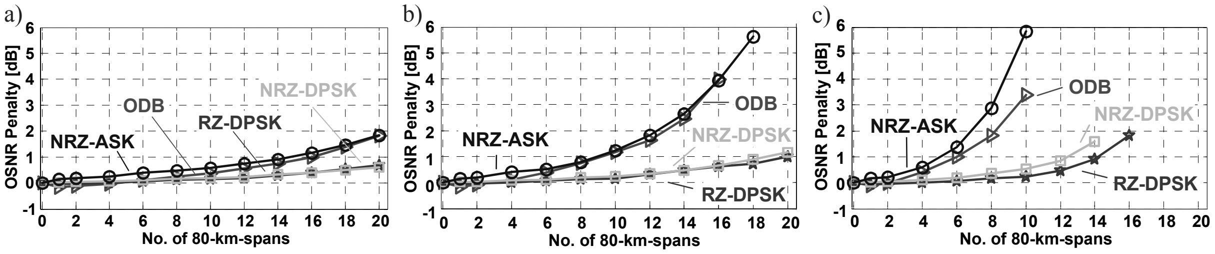

Figure 6: Penalty vs. spans for broadband FBG: a) -3 dBm/span b) 0 dBm/span c) 3 dBm/span.

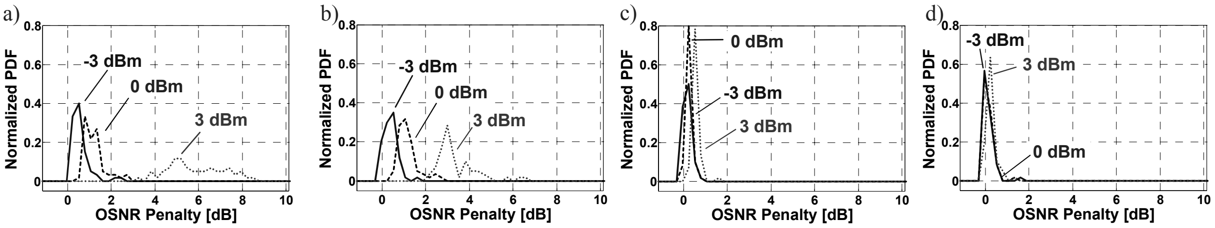

Figure 7: Probability density function of the OSNR penalty after ten spans with broadband FBG dispersion compensation for different fiber input powers: a) NRZ-ASK b) ODB c) NRZ-DPSK d) RZ-DPSK.

3.3 General Results

If a channelized FBG is applied, ODB performs best due to its narrow bandwidth. With the use of a broadband FBG DPSK shows the best results, while ODB is comparable to NRZ-ASK. DPSK is less sensitive to sinusoidal phase ripples than the other formats [3, 4] and more tolerant towards fiber nonlinearities. This explains the good results in a system with interaction of nonlinearities and phase ripples can be explained.

4. CONCLUSIONS

The performance of the 43 Gb/s system with FBG dispersion compensation strongly depends on the FBG type. If NRZ-ASK or DPSK modulation is applied in a system with channelized FBGs the FGBs have to be chosen carefully. A bandwidth of 60-70 GHz (or higher) and small shift between the channels might be tolerable. With smaller bandwidths and high shifts the filter bandwidths of the single pass bands will be too small and the ripples at their borders might have too much influence. RZ-DPSK is more sensitive to phase ripples and filtering than NRZ-ASK and NRZ-DPSK. For ODB modulation the channelized FBG shows satisfying performance up to 800 km (ten spans). In this case the penalty mainly results from phase ripples and not from amplitude filtering. The broadband FBG shows very good performance, especially if DPSK modulation is considered. Employing this FBG type, even the transmission of NRZ-ASK and ODB is possible over 20 spans with only 2 dB OSNR penalty. Moreover, it offers more flexibility since it has no limitations concerning the channel spacing.

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